Nondestructive Evaluation Education, Experiences and Career at NASA

ASNT Chapter Meeting
Brazosport College

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Part 2

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Agenda

- Organization of NDE at NASA
- Qualifications of NDE personnel at NASA
- NDE Requirements
- NDE Inspection
- NDE Methods
- NDE Method Application Examples
- POD Analysis
- Method Selection Factors
- Online Resources

Organization of NDE at NASA

- Centers with NDE Facilities
  - Johnson Space Center (JSC)
    - International Space station (Boeing), Orion (Lockheed Martin), Morpheus, Commercial Cargo/Crew (SpaceX Dragon/Falcon 9, Sierra Nevada Dream Chaser, Orbital Sciences, and Boeing CST-100)
    - JSC Engineering Contractor: Jacobs Eng. / JETS Contract
  - Marshall Space Flight Center (MSFC)
    - Space Launch System
  - Glenn Research Center (GRC)
  - Goddard Space Flight Center (GSFC)
  - Kennedy Space Center (KSC)
    - NDE Contractor: PaR systems (Former United Space Alliance, Hanger N NDE) supporting KSC launch/assembly operations and commercial activities
  - Langley Research Center (LaRC)
    - NDE Research Branch
    - NASA Engineering Safety Center, NDE Manager
    - NASA Headquarters Code Q NDE Manager
      - Also known as NASA NDE Working Group (NNWG)
        - » NASA Commercial Crew NDE Liaison
  - White Sands Test Facility
- Centers with NDE or IVHM
  - Each center has some of the two. Other centers are
  - Jet Propulsion Lab, Stennis Research Center, Armstrong Flight Research Center and Ames Research Center

Qualifications of NDE Personnel at NASA

- Civil Service
  - Ph. D.'s mostly at NASA LaRC
  - B.S. or M.S. in science, engineering, or mathematics
  - NAS 410 certified (NASA MSFC)
  - ASNT level 3 (MSFC and JSC)
- Contractor
  - NAS 410 required for part acceptance inspection
  - Formal education: high school diploma, AA, AS, BA, BS, MS, Ph. D.

NDE Requirements

- NDE is part of Materials and Processes Engineering
- NASA Programs at JSC
  - Requirements are program specific, for example
    - NASA-STD-6016 Standard Materials and Process Requirements for Spacecraft
    - NASA-STD-5019: Fracture Control requirements for Spaceflight Hardware
    - NASA-STD-5009: Nondestructive Evaluation Requirements for Fracture Critical Metallic Hardware
  - NAS 410
  - MIL-HDBK-6870
  - Data Requirements Document DRD: NDE Plan
- Commercial Programs with JSC involvement
  - Some of above requirements would be applicable as negotiated between NASA and the provider

NDE Inspection

- NDE Inspection
  - Routine NDE inspection is performed by Quality organization, Safety and Mission Assurance (S & MA) by NAS 410
  - Engineering personnel certified as NAS 410 may also perform the acceptance NDE
  - When authorized by program it may also be performed by NDE experts that are not NAS 410 certified

What is NDE?

- Nondestructive evaluation is a broad interdisciplinary field concerned with the development and use of inspection technologies to evaluate the integrity or measure a characteristic of a material, component or structure without impairing its future usefulness
- Common applications include:
  - Detection and sizing of defects in raw materials and manufactured components
  - Detection and sizing of in-service damage, e.g. fatigue cracks, corrosion and impact damage
  - Manufacturing process control
  - Assembly verification
  - Material verification and sorting
  - Coating thickness measurement
  - Physical, electrical and thermal property measurement
  - Stress measurement
- NDE is divided into various methods each based on a particular scientific principle (sound propagation in solids, thermal conductivity, electromagnetic induction, etc.)
- Each method is further divided into techniques based on the specific ways the method can be performed (ultrasonic pulse-echo, through transmission, contact, immersion); the total number of potential techniques is easily in the hundreds

NDE Methods

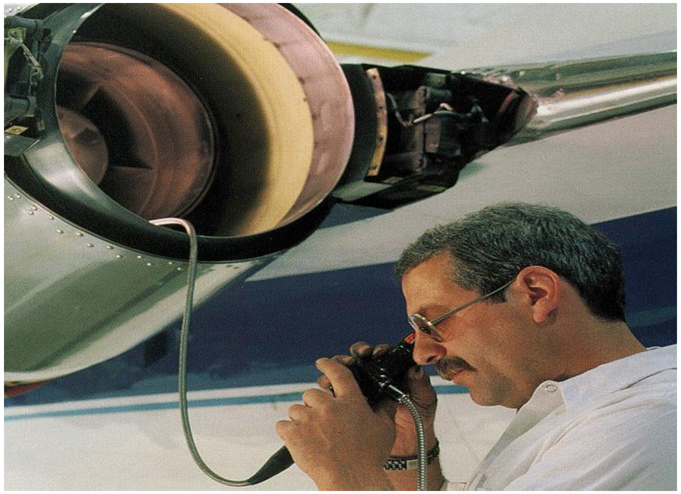
- Acoustic Emission
- Electromagnetic
  - AC Field Measurement
  - Eddy Current
  - Remote Field
- Ground Penetrating Radar
- Guided Wave
- Laser
  - Profilometry
  - Holography/Shearography
- Leak Testing
  - Bubble Testing
  - Pressure Change
  - Halogen Diode
  - Mass Spectrometer
- Liquid Penetrant
- Magnetic Flux Leakage
- Magnetic Particle
- Neutron Radiography
- Radiological
  - Radiography
  - Computed Radiography
  - Computed Tomography
  - Digital Radiography
- Thermal/Infrared
- Ultrasonics
  - Time of Flight Diffraction
  - Phased Array
- Vibration Analysis
- Visual

The Most Common Methods

- Visual (VT)
- Liquid Penetrant (PT)
- Magnetic Particle (MT)
- Eddy Current (ET)
- Ultrasonic (UT)
  - Phased Array (PAUT)
- Radiographic (RT)

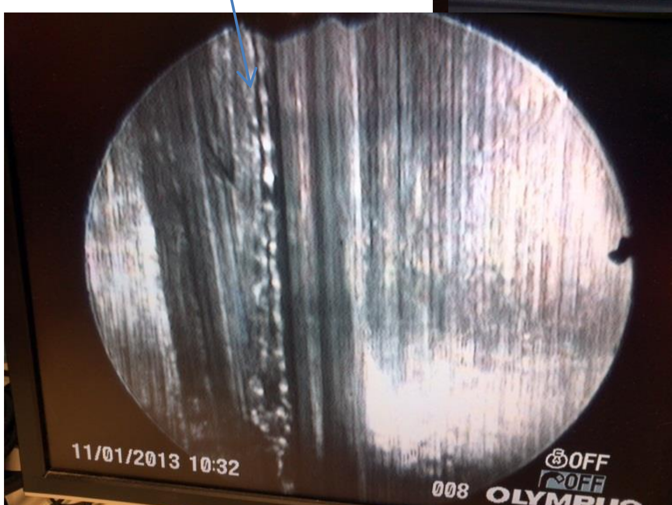
Visual Inspection

- Most basic and common inspection method used for detection of flaws visible on the surface of a part
- Tools include borescopes, magnifying glasses, mirrors, and video cameras



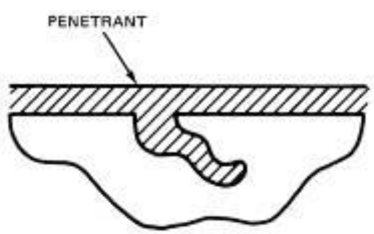
SAFER Welded Tubing Visual Inspection

Tubing weld



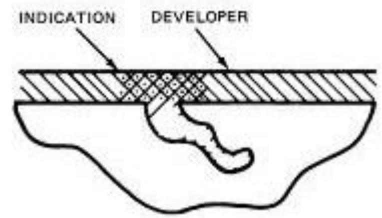
Dye Penetrant Testing

- Used for detection of flaws that are open or connected to the surface of a nonporous metal or nonmetal part
- Basic Process Steps
  1. Clean the part
  2. Apply penetrant
  3. Allow the penetrant to dwell for a minimum of 10 minutes
  4. Remove excess penetrant from the surface of the part
  5. Dry the part
  6. Apply developer
  7. Examine the part for indications a minimum of 10 minutes and a maximum of 60 minutes after the developer is applied
- Process details vary depending on the penetrant materials and equipment that are used.

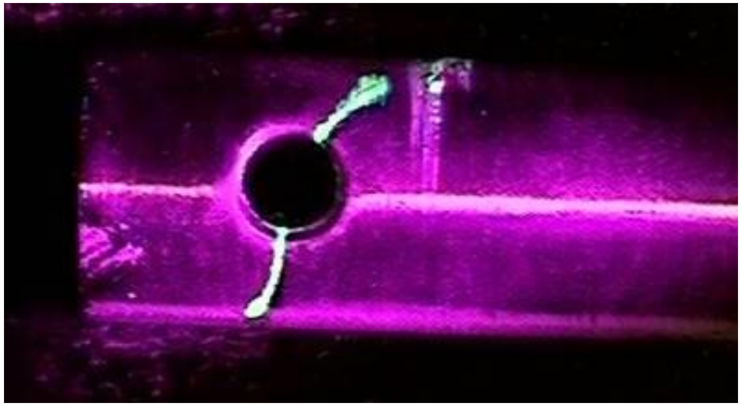


Apply Penetrant

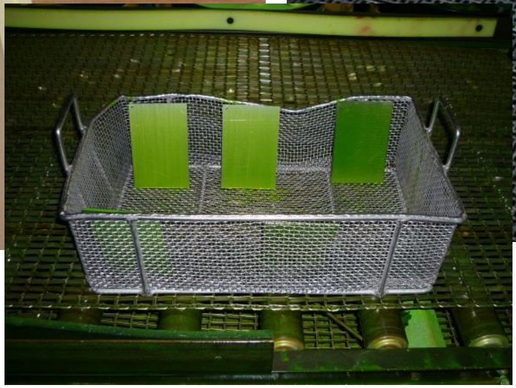
Remove Excess



Develop

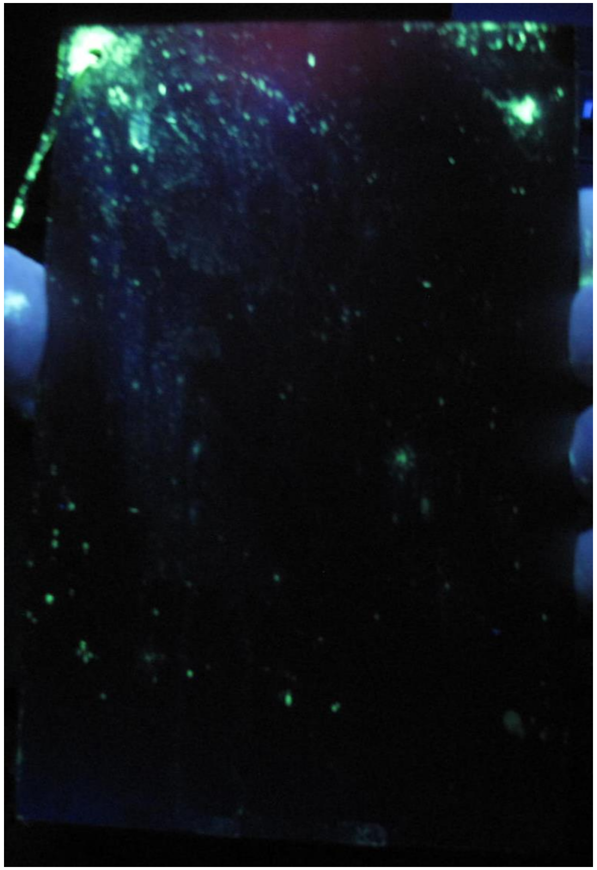


Dye Penetrant Testing

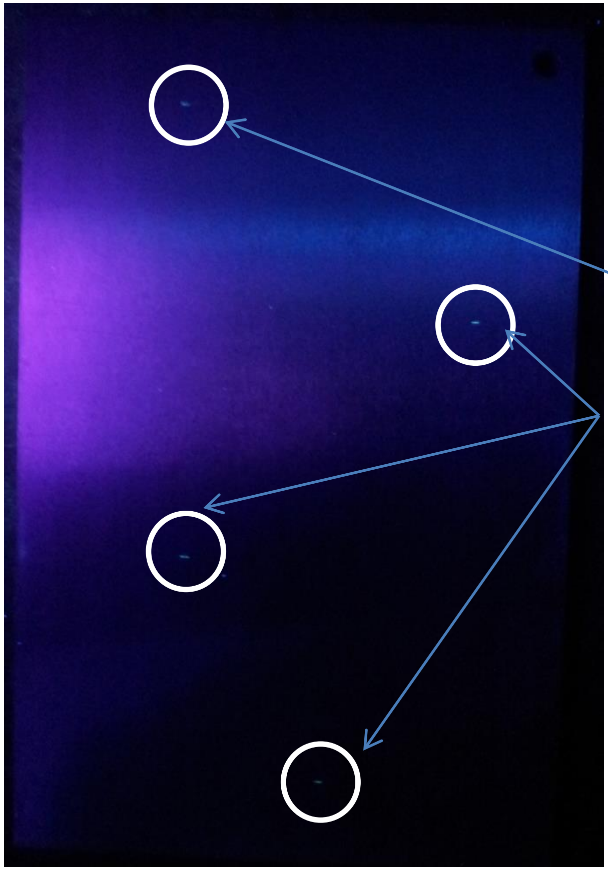


Dye Penetrant Testing

Excessive Background Fluorescence



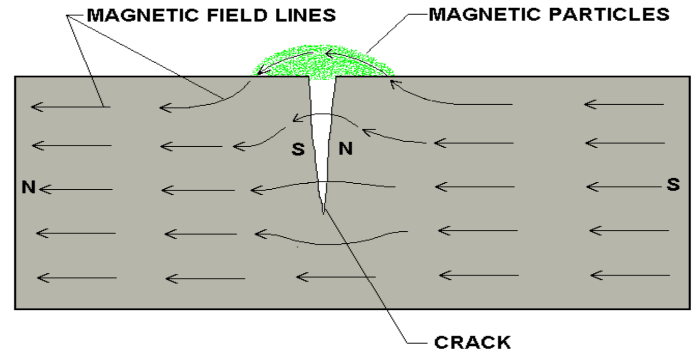
Ideal Background Fluorescence

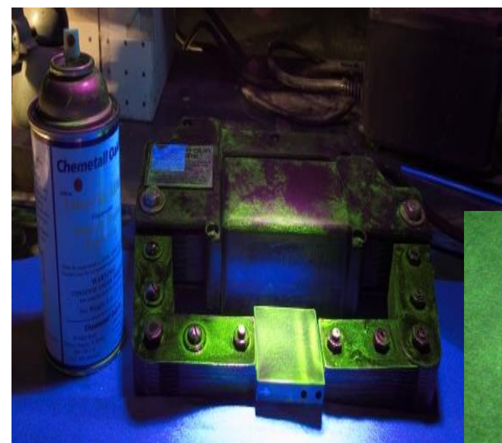


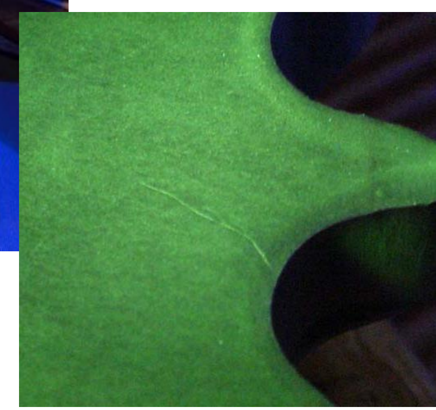
Fatigue crack indications

Magnetic Particle Testing

- Used for detection of surface or slightly subsurface flaws in ferromagnetic materials
- The part is magnetized ; AC or DC, circular or longitudinal
- Finely milled iron particles coated with a dye are applied to the part
- The particles are attracted to magnetic flux leakage fields and will cluster to form a visible indication directly over the discontinuity
- Flaws are difficult to detect when they make an angle of less than 45° to the direction of magnetization
  - For this reason, parts are normally magnetized in at least two perpendicular directions

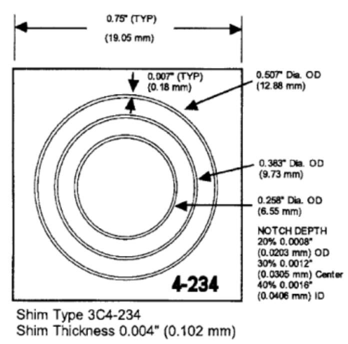






Magnetic Particle Testing

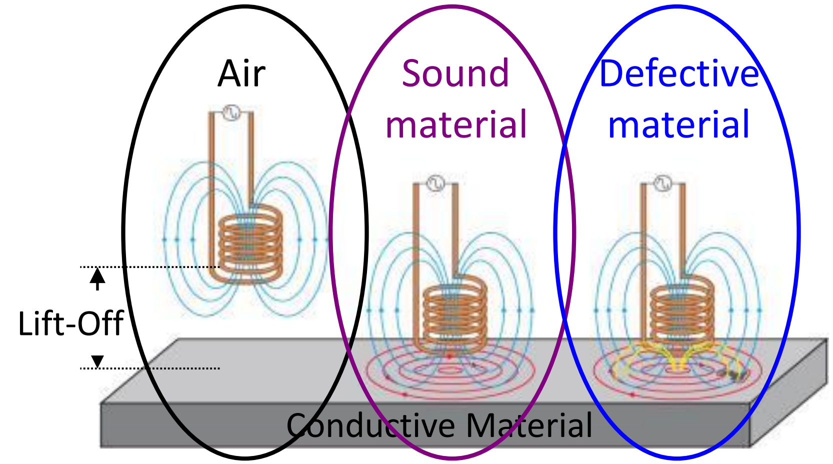
- Verification of appropriate magnetic field direction and strength is vital
  - The tangential field strength measured at the part surface should be a minimum of 30 Gauss (3 mT)
- Four commonly used methods:
  - Flexible laminated strip (field direction only)
  - Pie gauge (field direction only)
  - Notched shims (QQI)
  - Hall effect probe (gauss meter)
- Cannot depend on the formulas – they're only meant for simple part geometries
  - Fields in complex parts can cancel each other out!
- A QQI or gauss meter are the only reliable methods

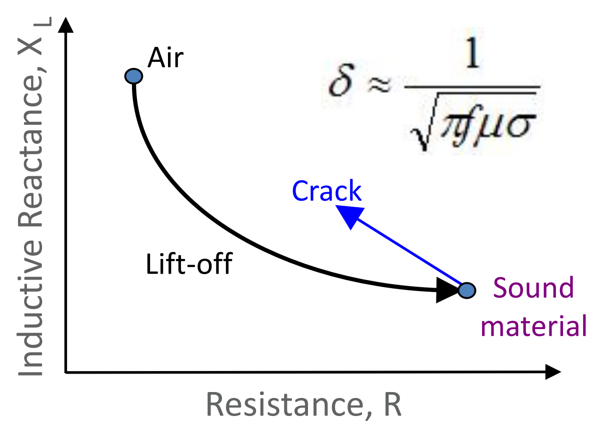


Portable Magnetic Particle Inspection Kit

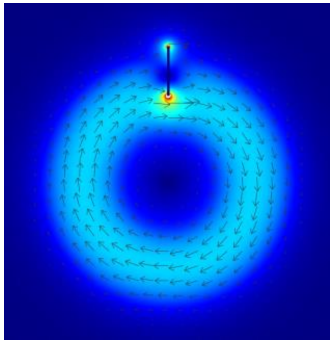
Eddy Current Testing

- Used for detection of surface and subsurface flaws in electrically conductive materials
- An AC current is passed through a wire coil producing a primary alternating magnetic field around the coil
- When the primary magnetic field intersects a conductive material, oscillating eddy currents are induced in the material
- The eddy currents produce a secondary magnetic field which interacts with the primary field and changes the coil's impedance
- Flaws will disrupt the flow of eddy currents which in turn disrupts the secondary magnetic field and ultimately the coil's impedance

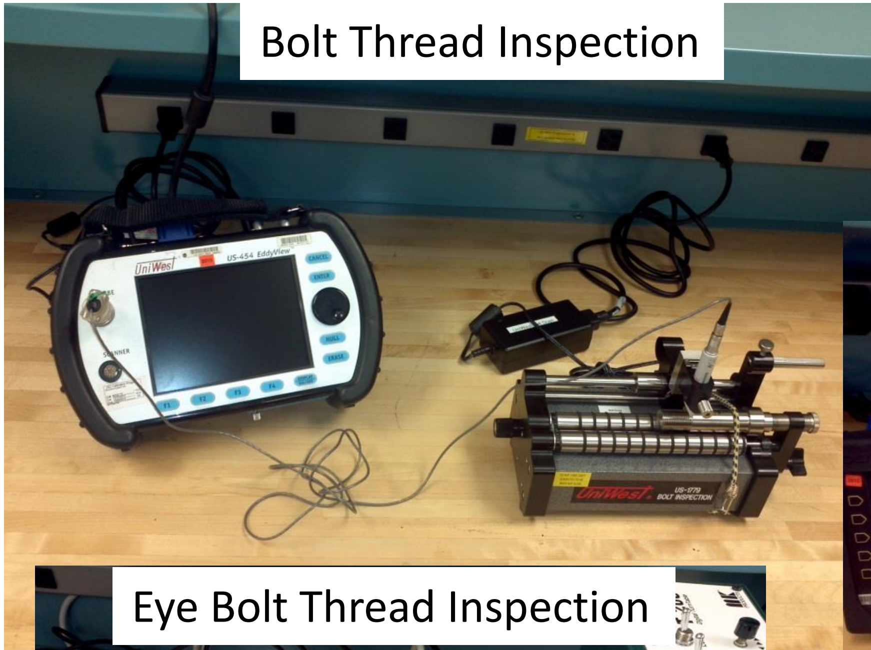




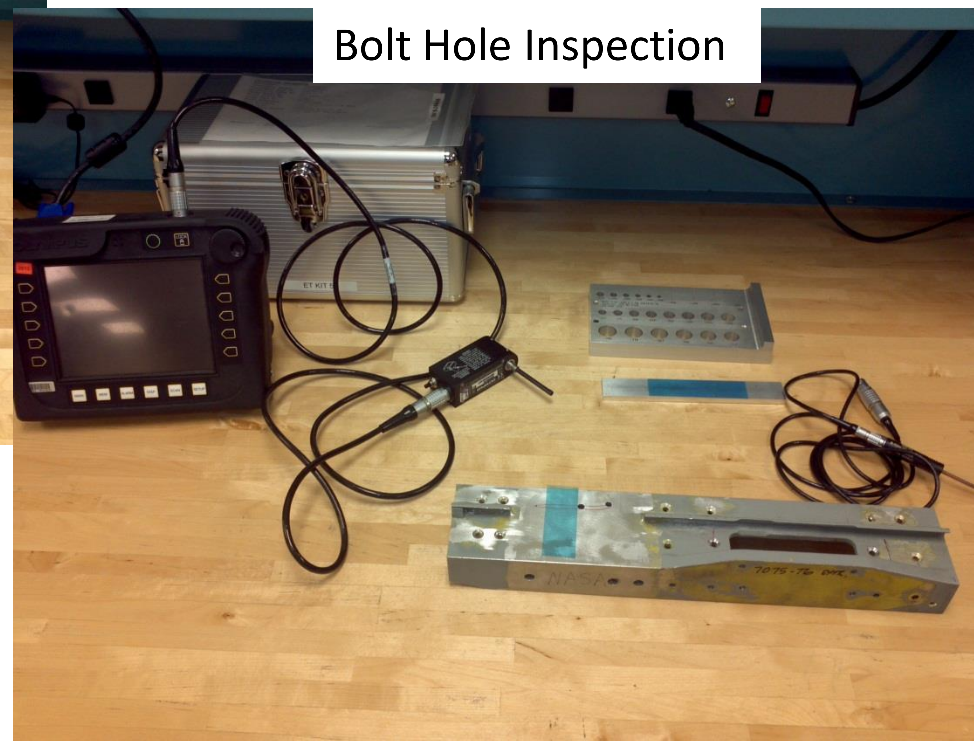
$$\delta \approx \frac{1}{\sqrt{\pi f \mu \sigma}}$$



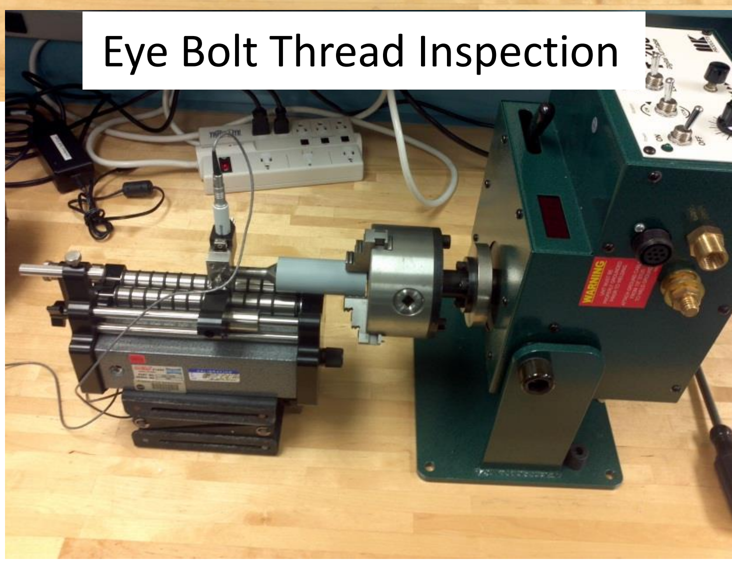
Eddy Current Testing



Bolt Thread Inspection



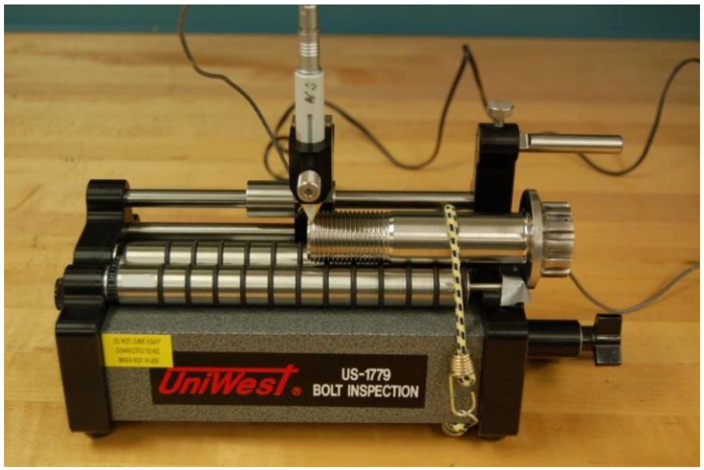
Bolt Hole Inspection



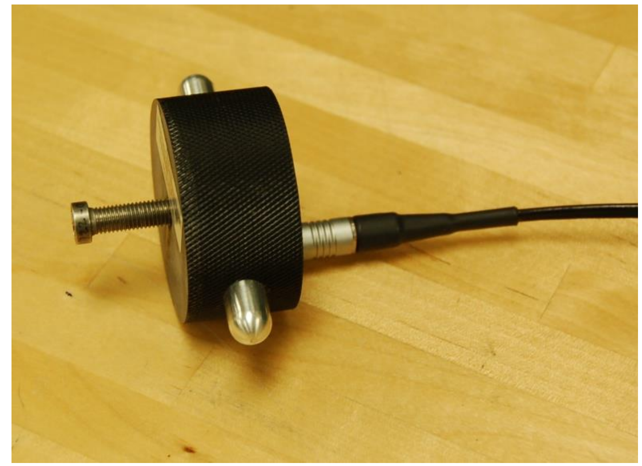
Eye Bolt Thread Inspection

NDE Laboratory Scanners and Probes

Bolt Scanner



"Nut" Type Bolt Probe

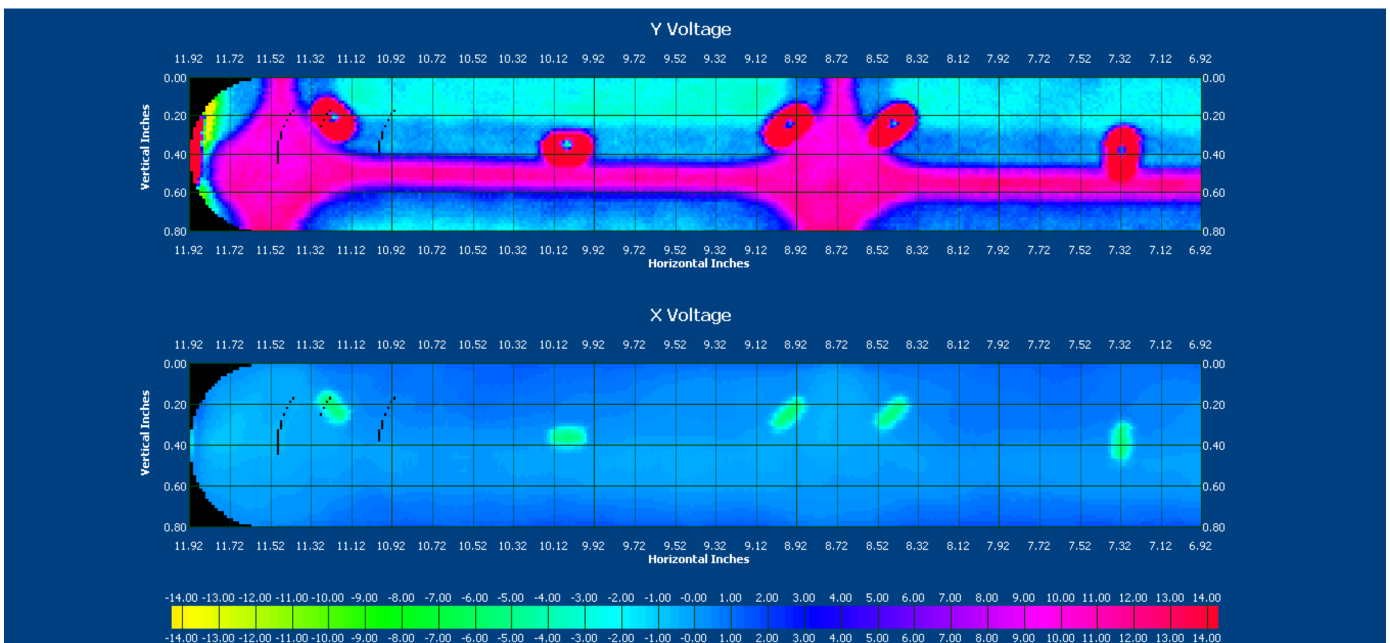


Bolt Hole Scanner

Array Probes

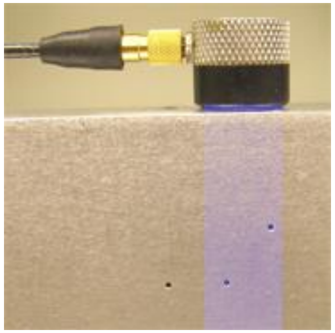
UniWest ECS-3 Rotating Scanner

- Russian ISS Pressure Wall (Aluminum; 0.0625” skin thickness; 0.438” rib thickness)
- 12 kHz test frequency
- 0.1” long x 0.020” deep backside EDM notches in the skin

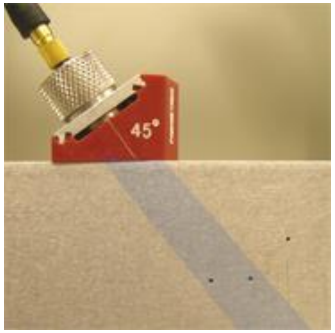


Ultrasonic Testing

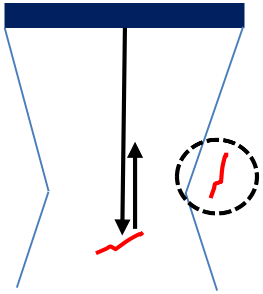
- Used for detection of surface and subsurface flaws in metals, nonmetals and composites
- Conventional transducers use a single piezoelectric element to transmit and receive high frequency (1 to 15 MHz) sound waves, typically longitudinal (compression) or transverse (shear)
- The sound beam is unidirectional and divergent although focusing is possible using specialized transducers
- For maximum response, the direction of sound propagation must be perpendicular to the plane of the flaw
- Accept/reject decisions are usually made based on a comparison of the signal amplitudes produced by the flaw and a specified reference reflector, typically a drilled hole or EDM slot



0° Longitudinal

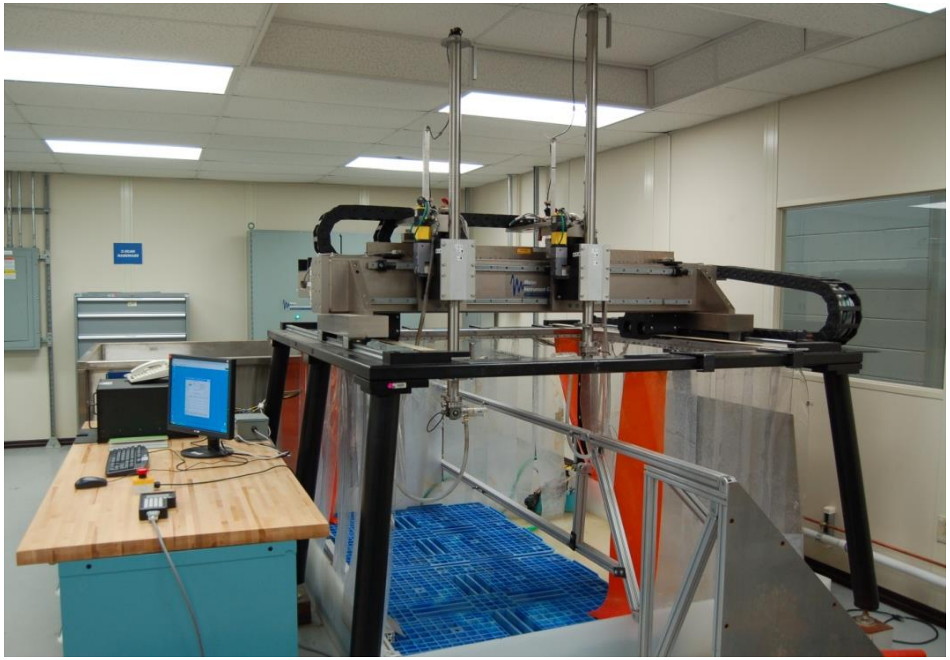


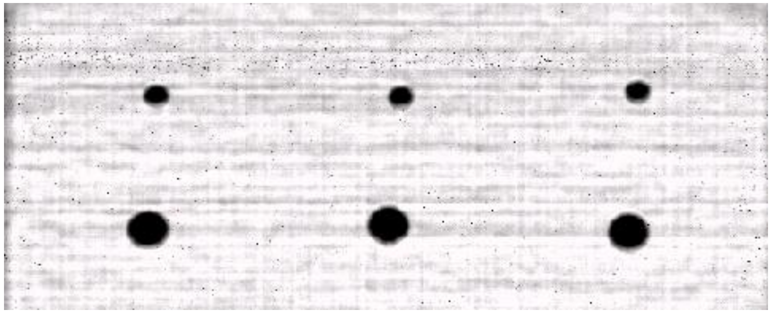
45° Shear



A-Scan

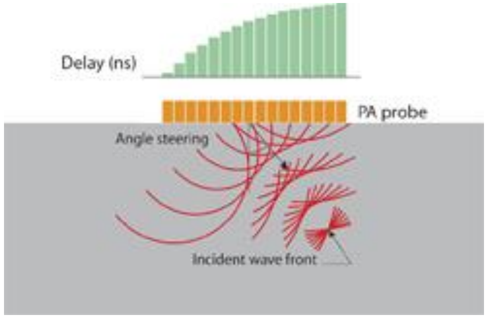
Matec Immersion/Bubbler Scanning System

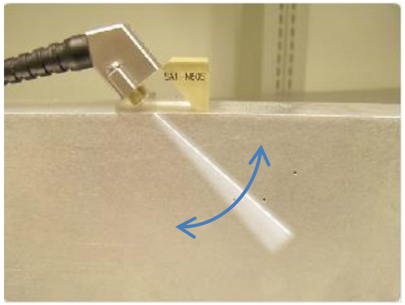


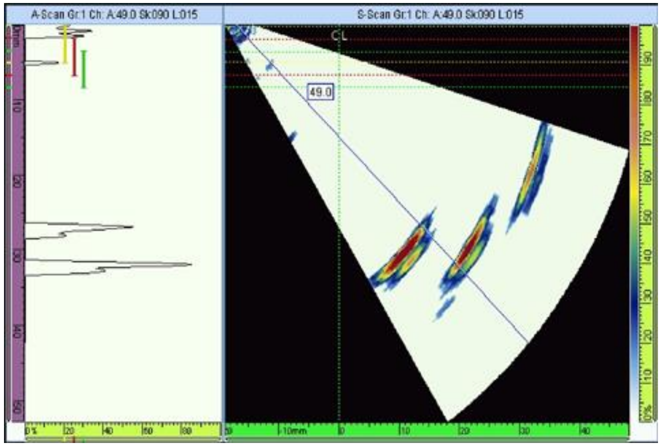


Ultrasonic Phased Array Testing

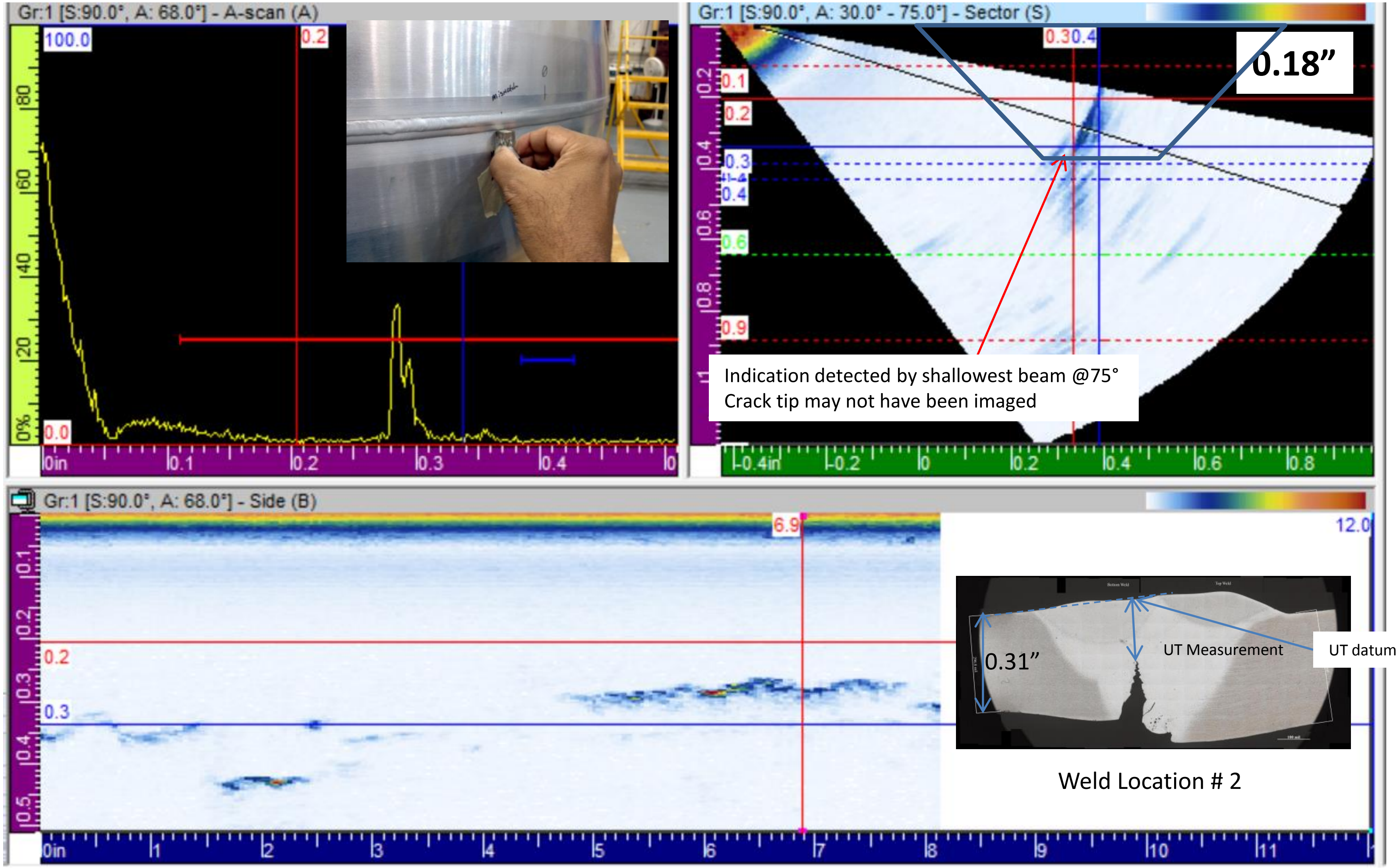
- Phased array transducers contain between 10 and 256 piezoelectric elements that can be individually pulsed
- By pulsing the elements at slightly different times, the ultrasonic waves produced by each element will combine through constructive and destructive interference to form a sound beam at a specified angle and focus depth
- Electronic beam steering makes it possible to sweep the sound through a range of angles or along a linear path
  - Increases the volume of material inspected from a single transducer position
  - Increases the chances that a flaw will be intersected by a beam at the optimum angle for detection
- Electronic focusing increases the chances of detecting smaller flaws at a greater range of depths
- Data is typically displayed as a 2-D cross-sectional view with signal amplitude plotted as a function of beam angle, depth in the part and distance from the front edge of the transducer (S-Scan)



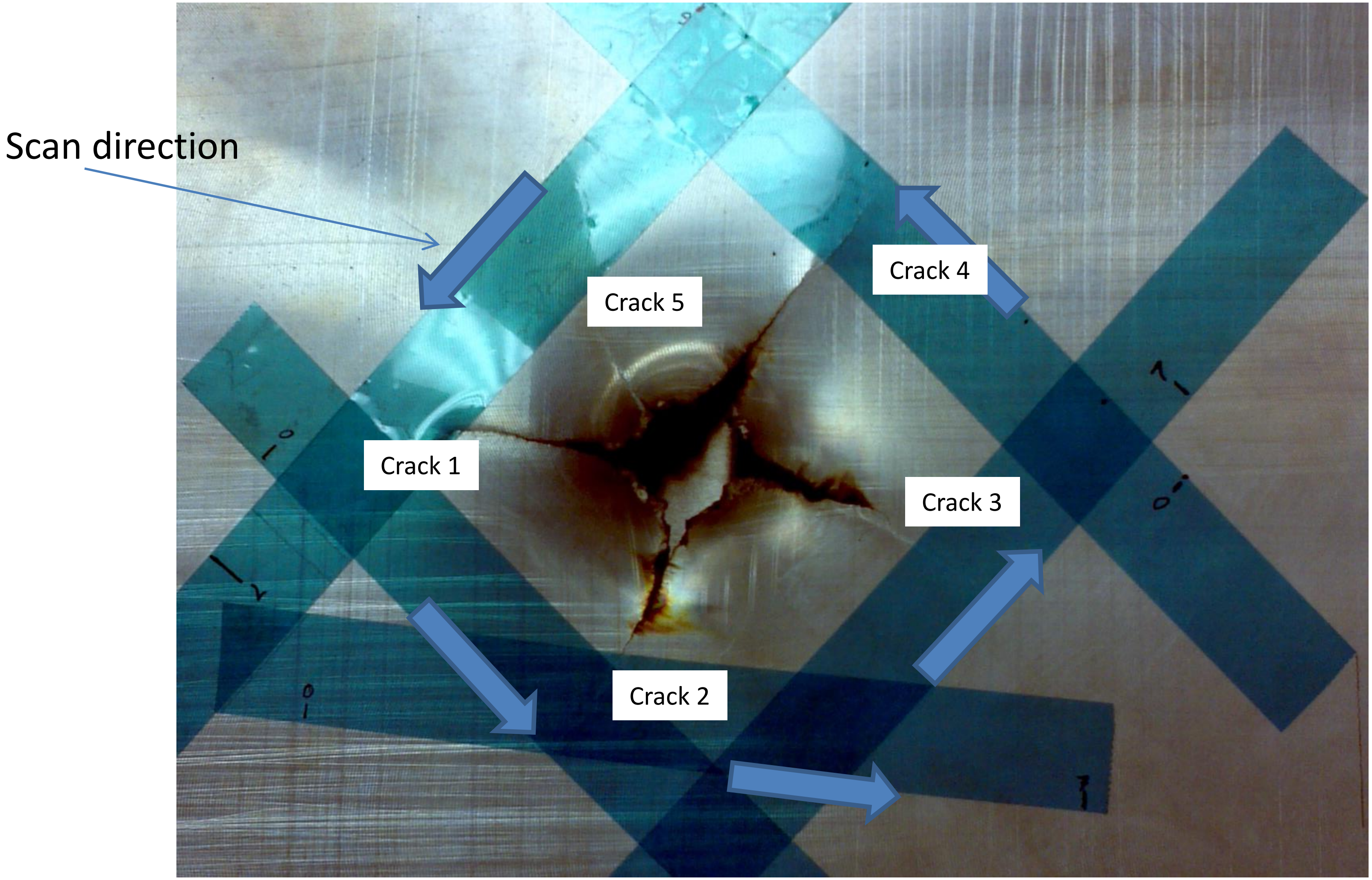




Phased Array Inspection of Girth Weld



Scan Path Markings on the Part Surface

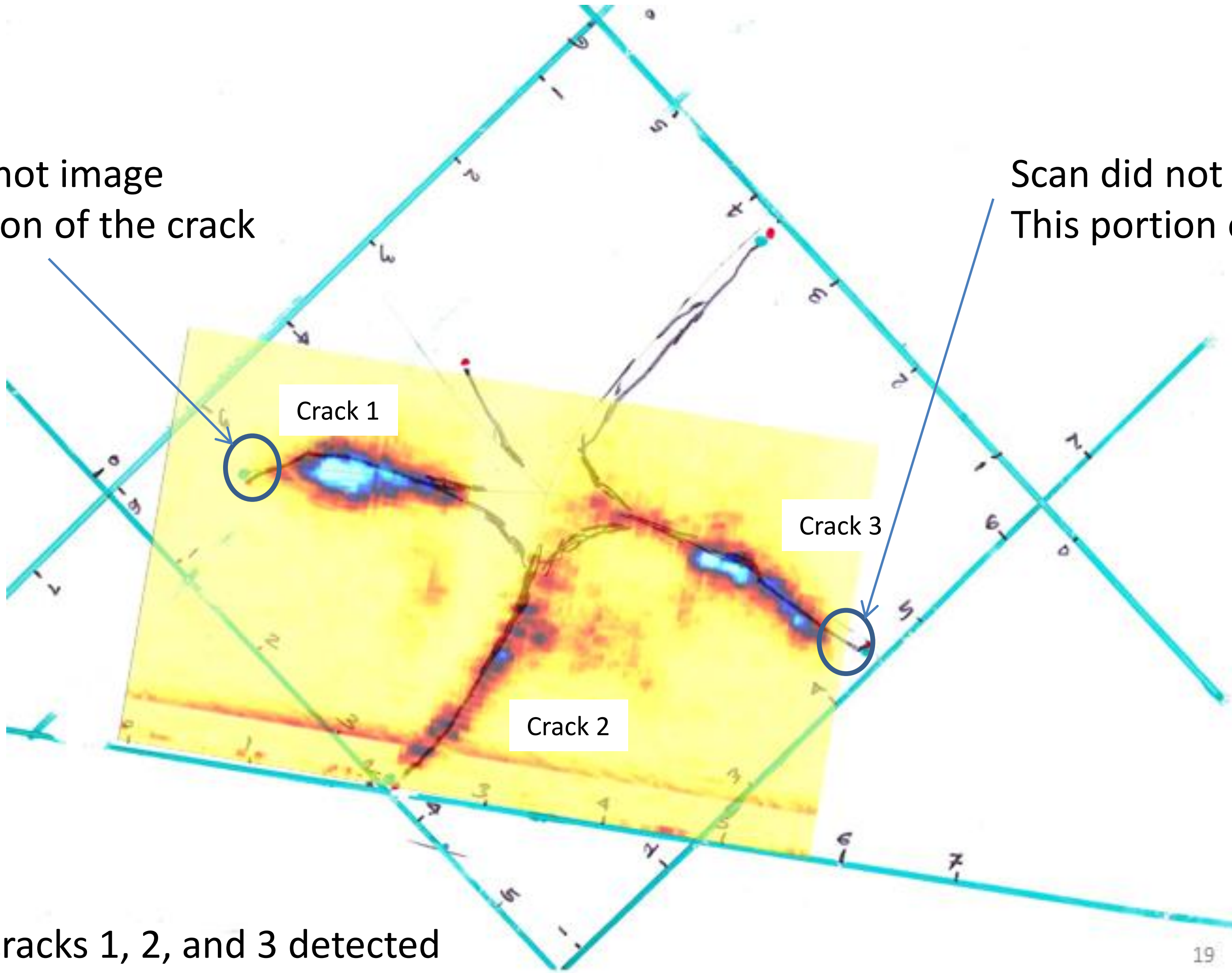


Superimposed on Hand Trace of Cracks on Ultrasonic Phased Array Testing Results

Nondestructive Evaluation Laboratory

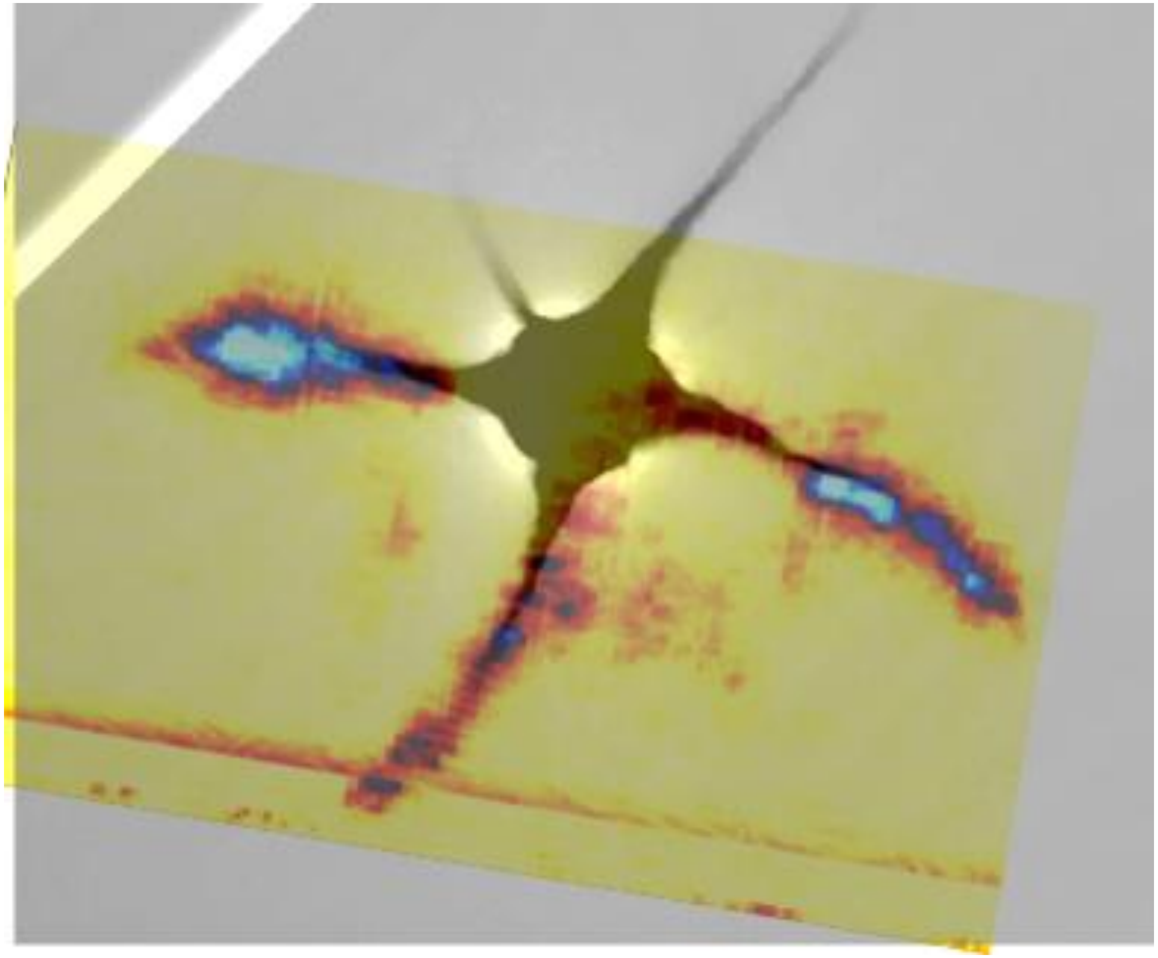
Scan did not image
This portion of the crack

Scan did not image
This portion of the crack



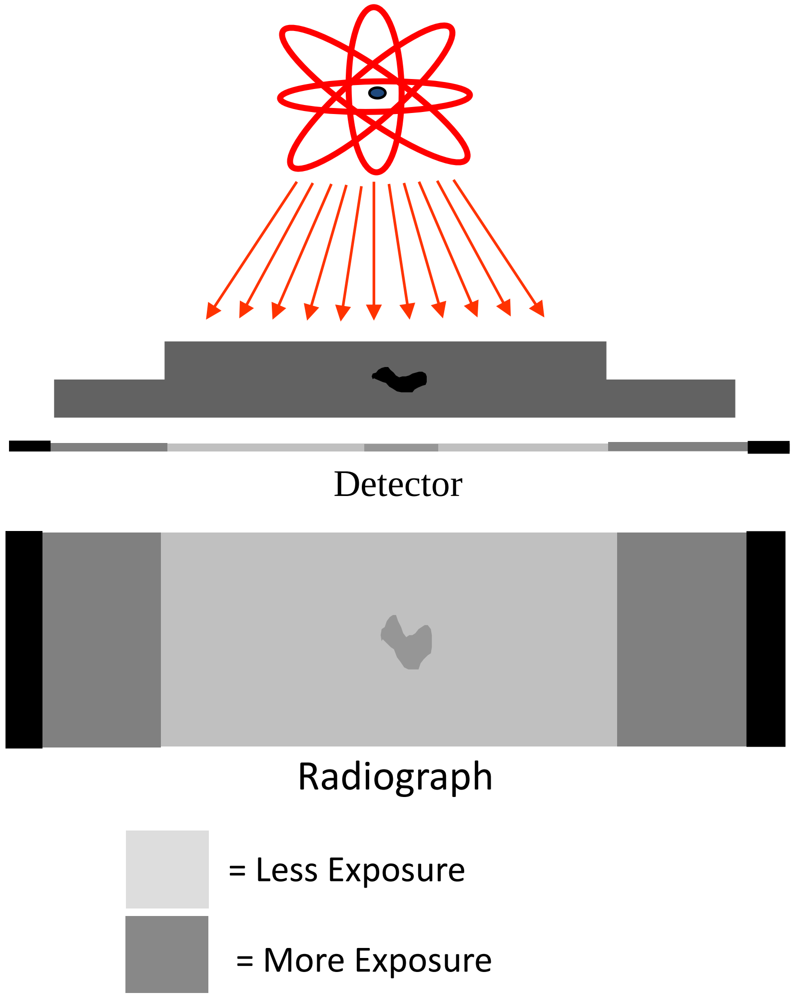
Cracks 1, 2, and 3 detected

Ultrasonic Phased Array Testing Results Superimposed on Digital X-ray

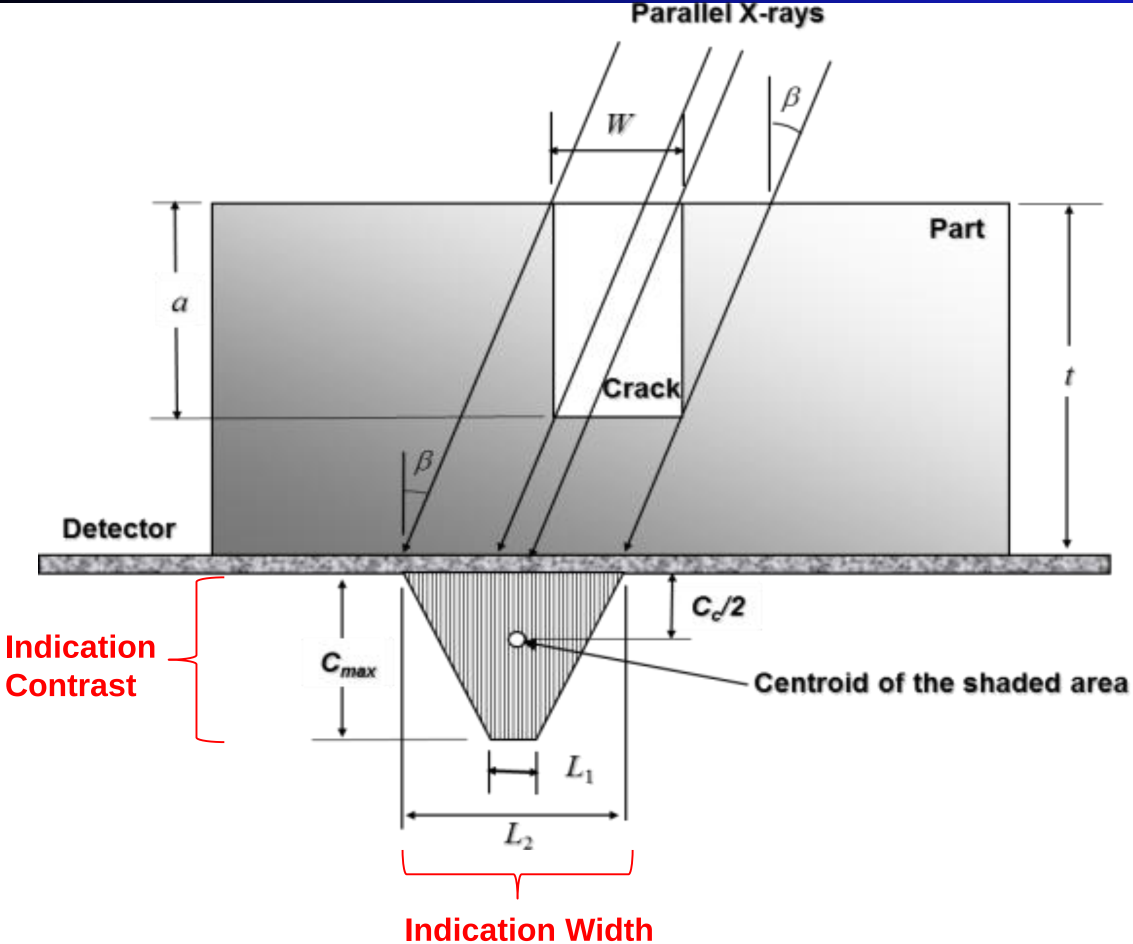


Radiographic Testing

- Used for detection of subsurface flaws, assembly verification and FOD detection
- Applicable to most materials
- Ideal for detecting three dimensional (volumetric) flaws such as porosity, voids, high and low density inclusions
- Considered a poor method for fatigue crack detection (crack must be aligned with the radiation beam)
- Utilizes penetrating radiation (X-rays, Γ-rays, neutrons) to expose discontinuities in materials
- Requires access to both sides of the part for radiation source and detector placement
  - X-ray backscatter is an exception
- There are a variety of detector options: film, phosphor plates (CR), flat panel DR detectors - amorphous silicon & amorphous selenium, and CMOS



Cross Sectional Geometry of Part, Slot, and X-ray Shadow Profile on the Detector

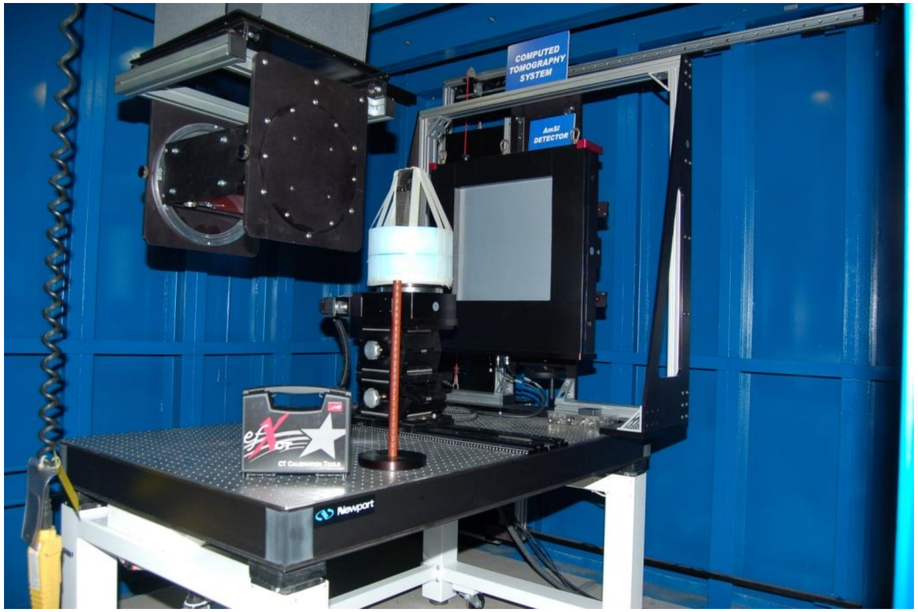


Visual detection of a fine flaw like a crack is based on contrast magnitude

The rectangular cross sectional area of the
crack is mapped as a trapezoidal area

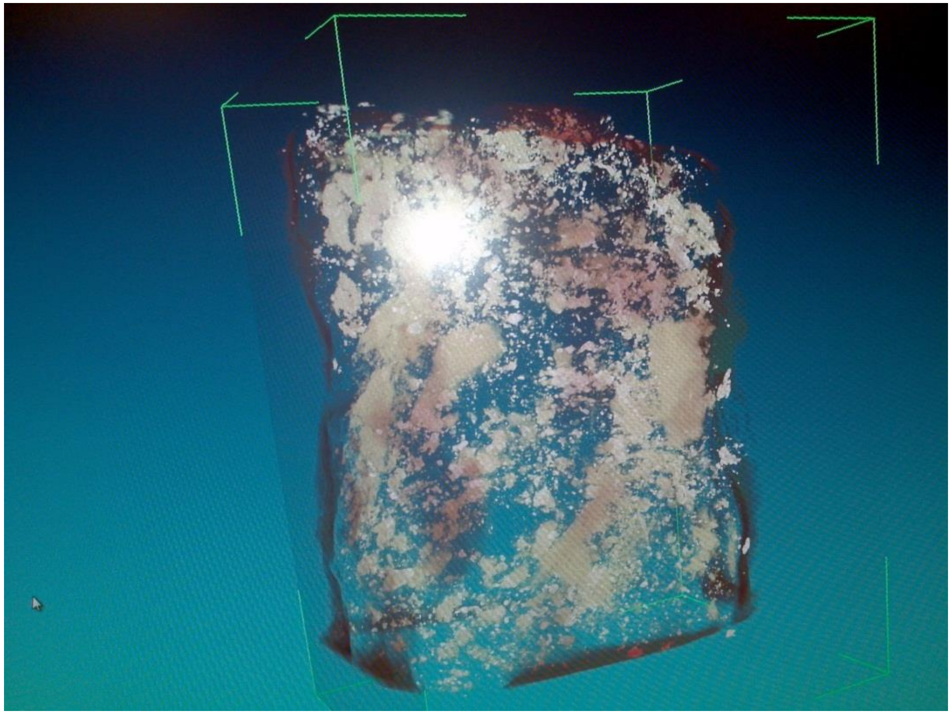
Cross Sectional Geometry of Part, Slot, and X-ray Shadow Profile on the Detector

Computed Tomography/Digital Radiography



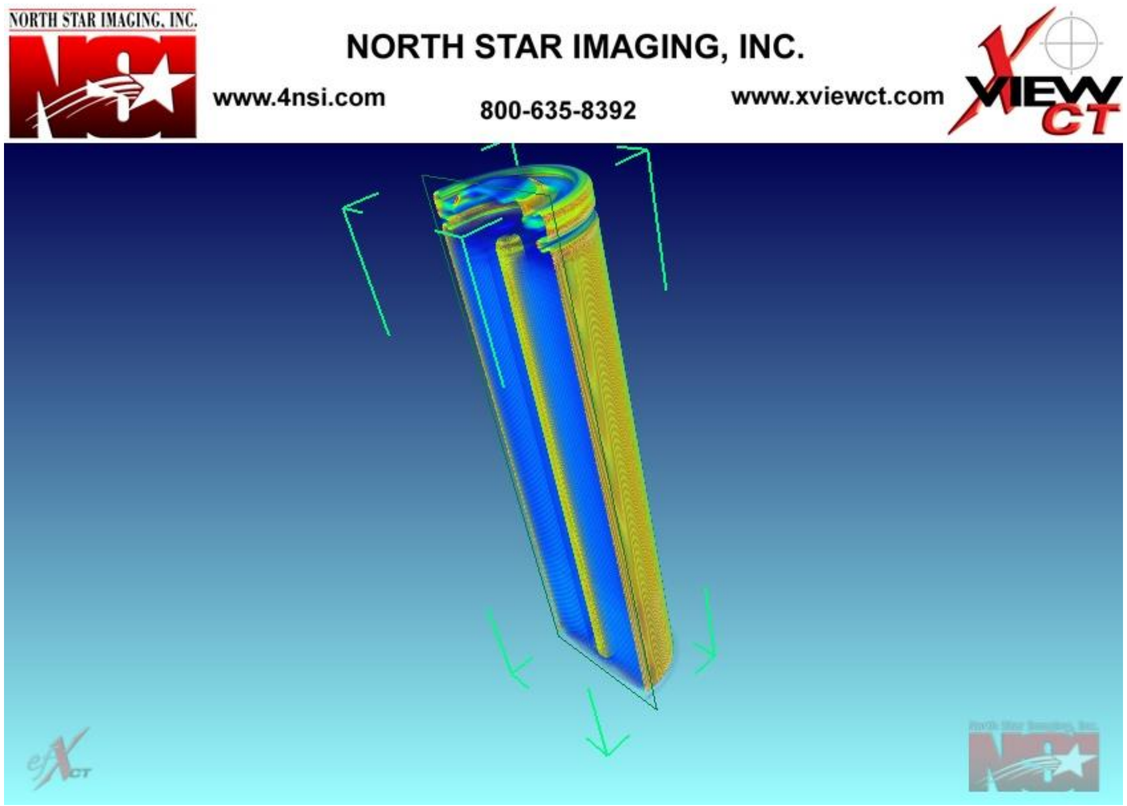
X-ray Computed Tomography of Rock

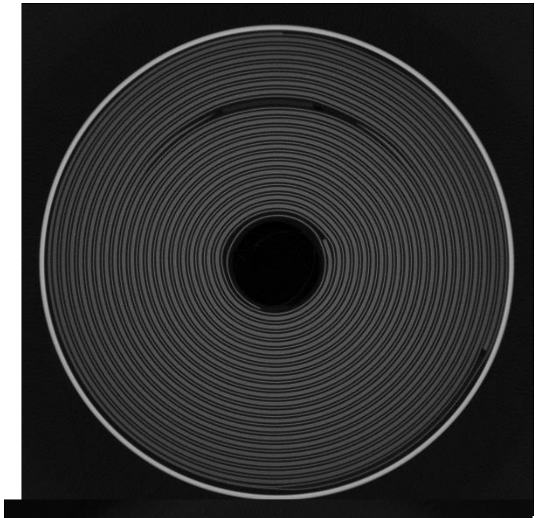
X-ray CT Image

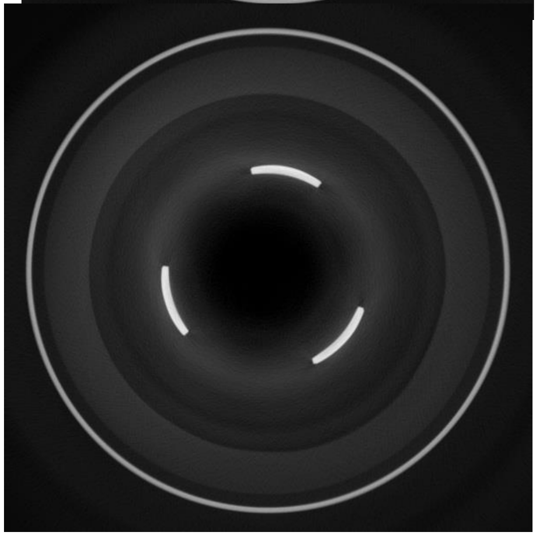


The Critical Role of High Resolution X-ray Micro-computed Tomography for Ultra-thin Wall Space Component Characterization, D. J. Roth, R. W. Rauser, R.R. Bowman, R.E. Martin, A. M. Koshti, and D. S. Morgan, Materials Evaluation, March 2014, page 383.

X-ray Computed Tomography of Li-Ion Battery







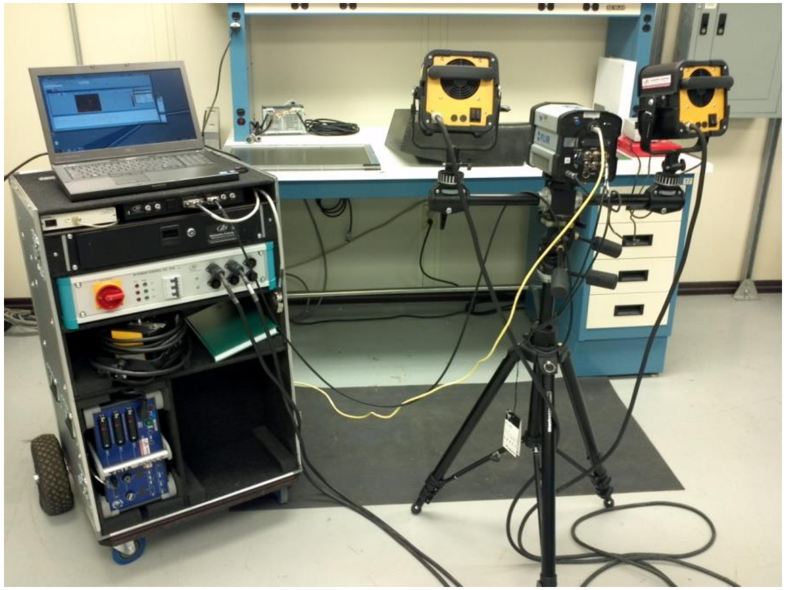
Additional Methods

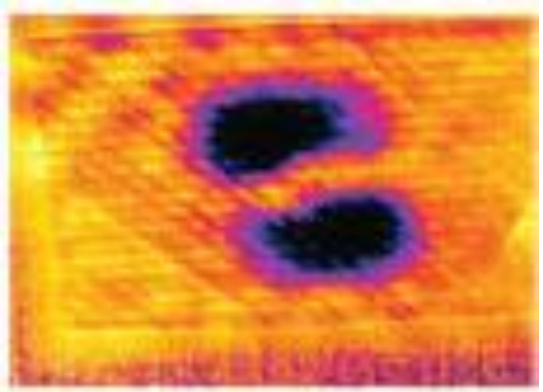
- Infrared Thermography
- Laser Shearography
- Optical 3D Deformation Analysis (Aramis)
- High Speed Video
- X-ray Fluorescence (XRF) Spectrometer

Infrared Thermography

- Used for detection of subsurface flaws in composites and bonded structures
- Heat is applied to the surface of a part and an infrared camera is used to record changes in the surface temperature (irradiance)
- The surface temperature is affected by internal flaws such as disbonds, voids and inclusions which obstruct the flow (conduction) of heat through the part
- The obstructed heat flow is observable as a hot or cold spot on the part surface
- A number of heat sources are used for camera side or backside heating: flash lamps, heat lamps, heat guns, vibration, electromagnetic inductance

MoviTherm Composite-Check IRT System





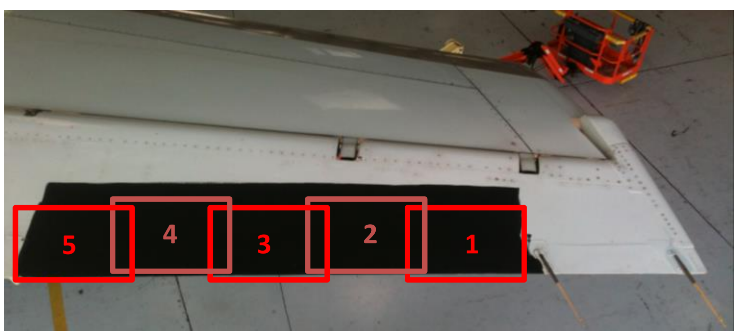
Space Shuttle Orbiter Flash IR Inspection

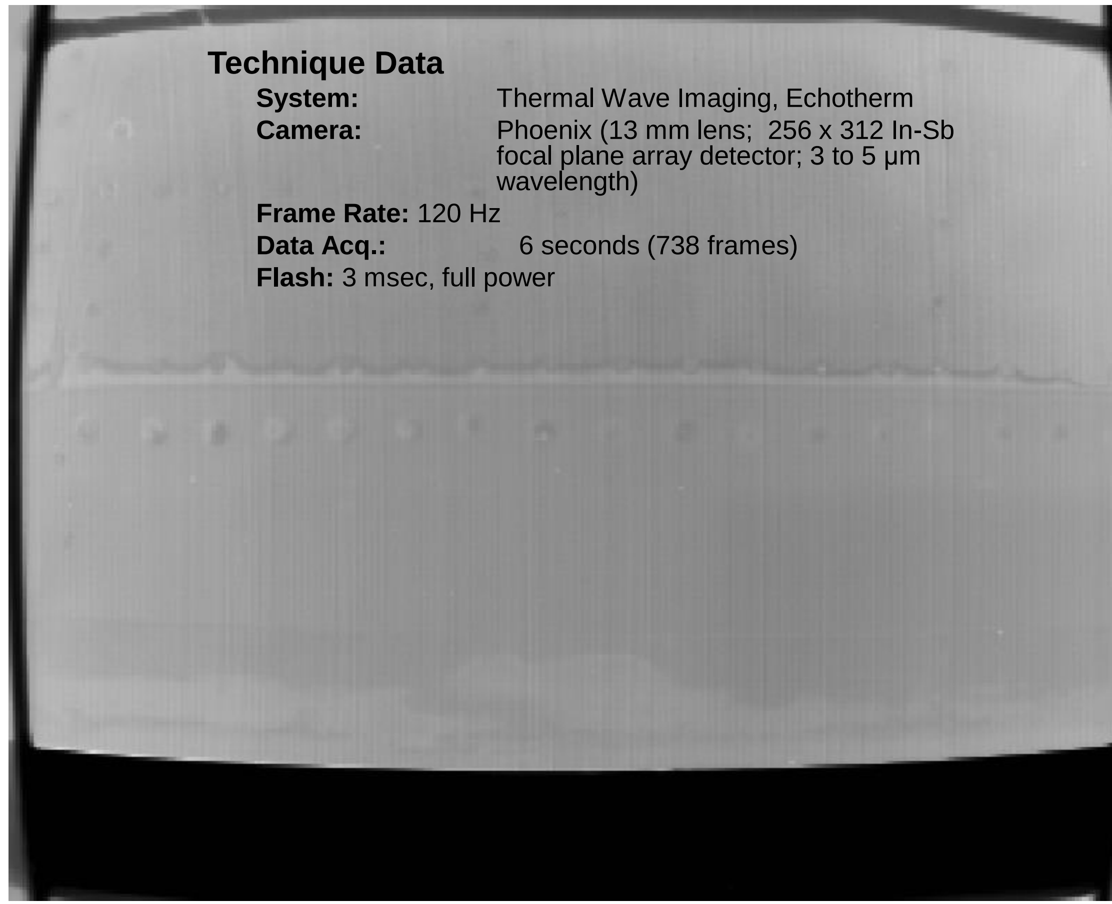
RCC Panel IR Inspection at JSC

Orbiter RCC inspection in Orbiter Possessing Facility at KSC

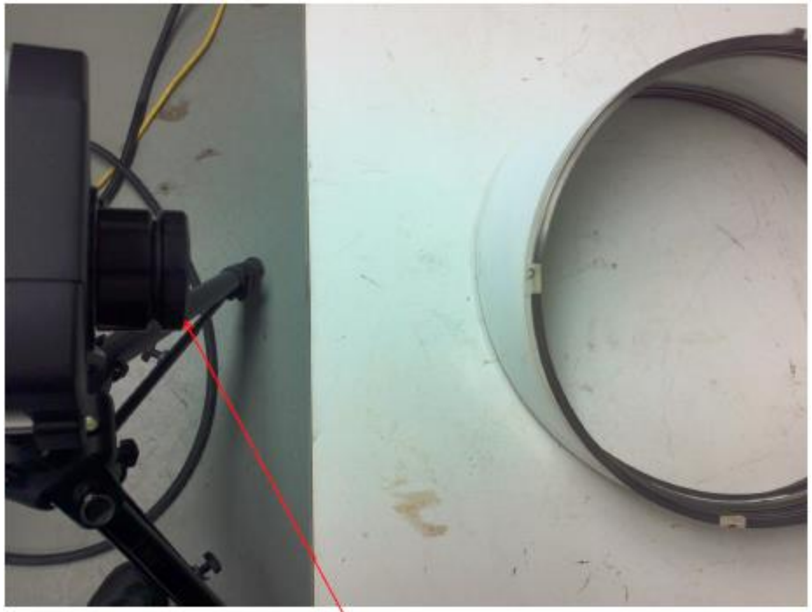
Flash IR Hood attached to Strong Arm that is attached to a cart on rails.
Worked as a project engineer to develop and implement IR thermography Inspection of Orbiter wing leading edge at Kennedy Space Center

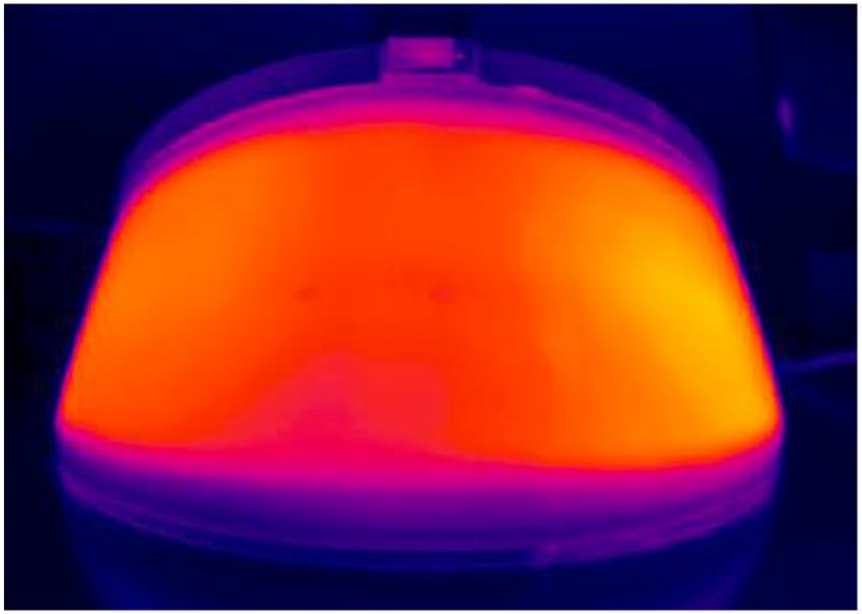
Flash Thermography of the DC-9 Elevator Closeout Panel (Upper Side Shot 5)



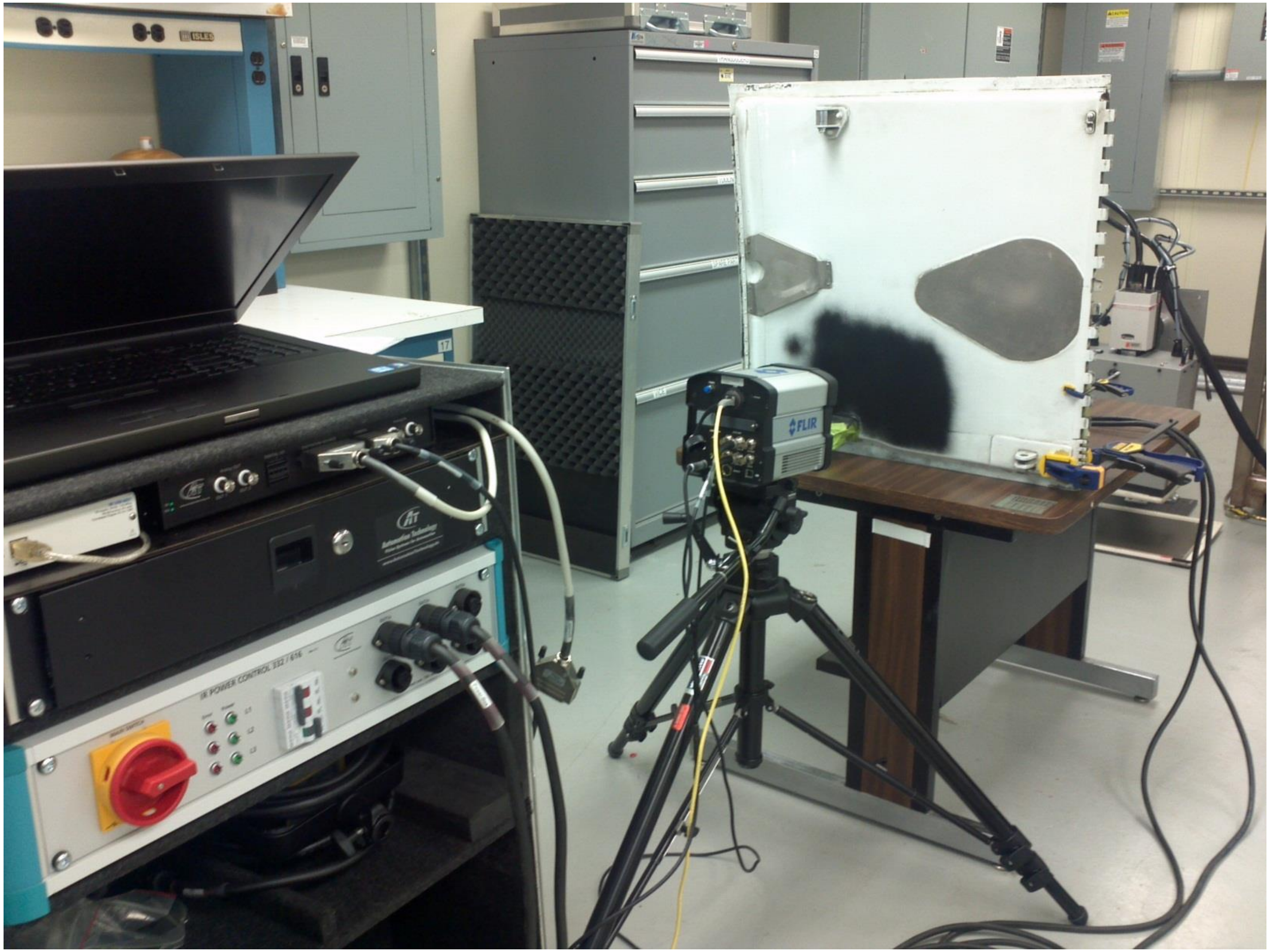


Infrared Inspection of Mark III Spacesuit Link

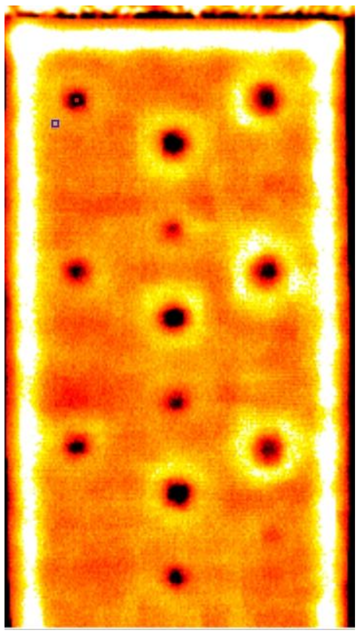




MoviTherm System: Inspecting T-38 Door Panel

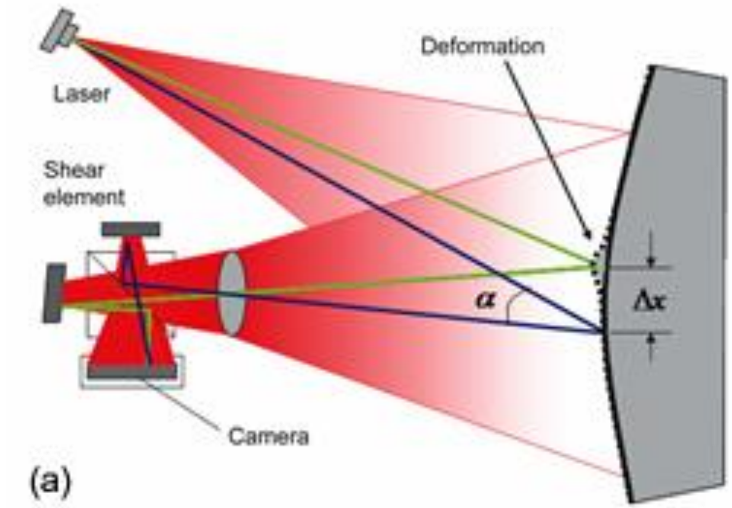


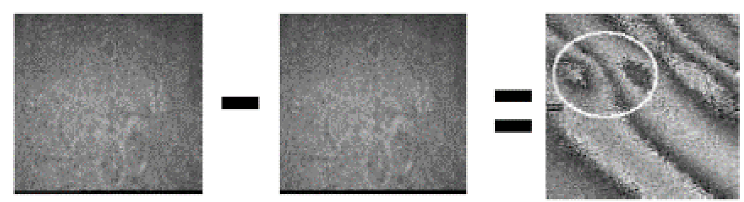
Infrared Flash Thermography Contrast Analysis



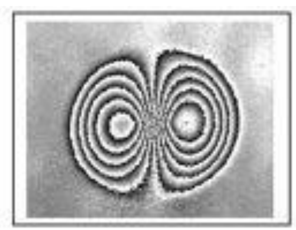
Laser Shearography

- Used for detection of subsurface flaws in composites and bonded structures:
  - Disbonds
  - Delaminations
  - Porosity
  - Foreign objects
  - Impact damage
- Basic Principle
  - An unloaded part is illuminated with a laser producing a speckle pattern which is captured by a digital camera
  - Before the image reaches the camera, it is doubled, laterally sheared (shifted) and superposed creating a double image of the part (shearogram)
  - The part is then loaded and a second shearogram is generated
  - The two shearograms are then subtracted to create an image showing the first derivative of any out-of-plane surface deformation (“butterfly” fringe pattern) due to the presence of a flaw

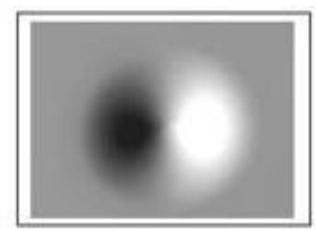




Unloaded Loaded Result



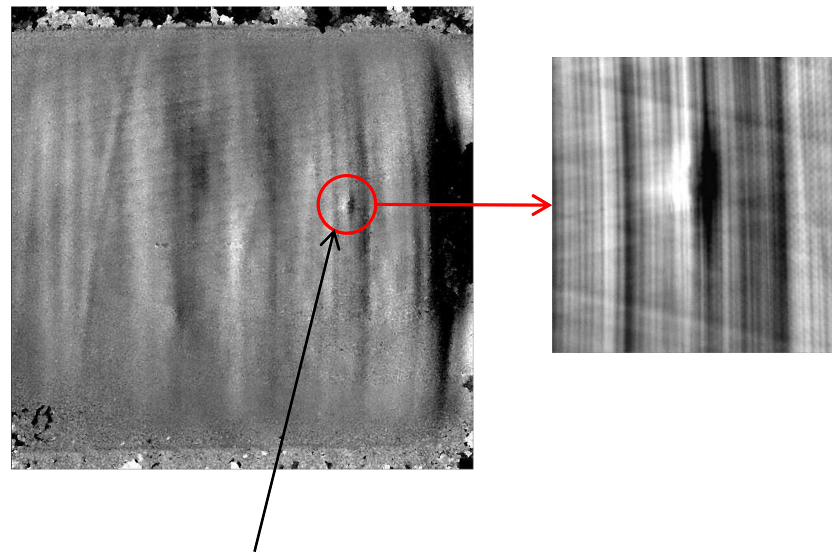
Wrapped



Unwrapped

Laser Shearography:
Inpedction of Linerless Composite Tank

Inspection of a Microcosm Linerless Composite Tank at WSTF using the Laser Technology Inc. Shearography System



Suspect anomaly

Optical 3D Deformation Analysis

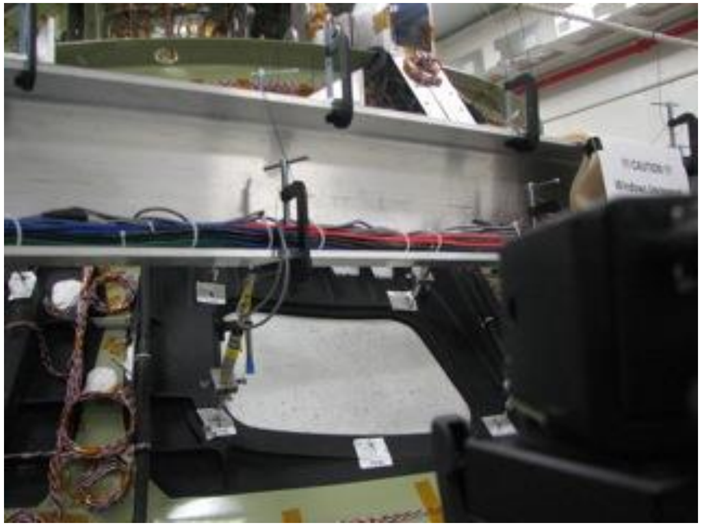
ARAMIS

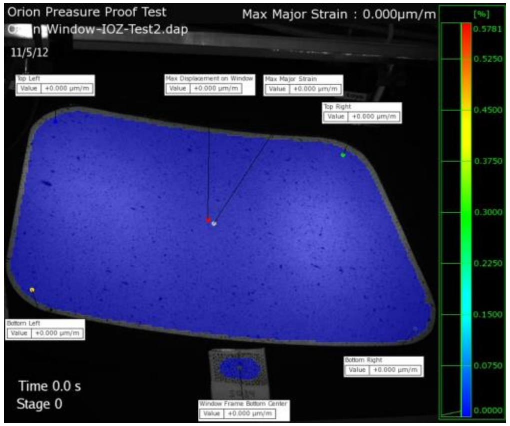
ARAMIS is a non-contact optical 3D measuring system capable of analyzing, calculating and documenting deformations. ARAMIS is suitable for three-dimensional deformation measurements under static and dynamic loads.

Fields of Application

- Material testing
- Strength assessment
- Component dimensioning
- Examination of non-linear behavior
- Characterization of creep and aging processes
- Determination of Forming Limit Curves (FLC)
- Verification of FE models
- Determination of material characteristics
- Analysis of the behavior of homogeneous and inhomogeneous materials during deformation
- Strain computation

Orion Window Proof Pressure Test





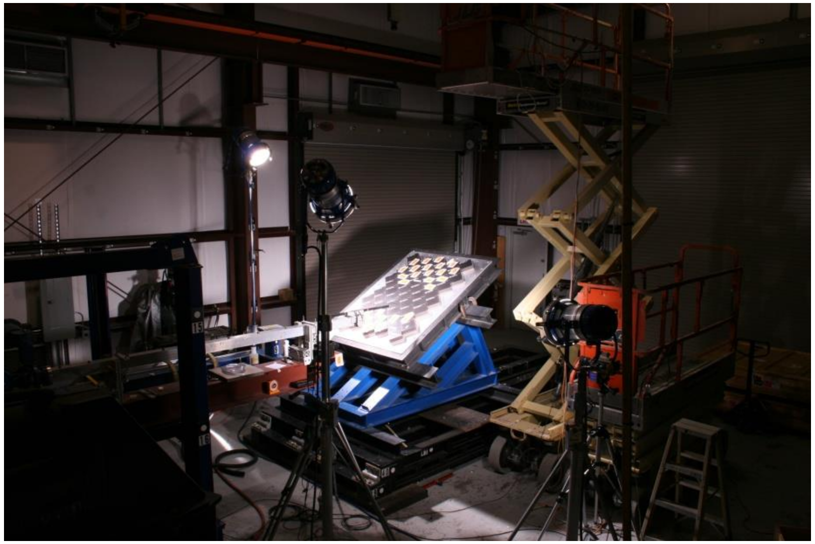
High Speed Video

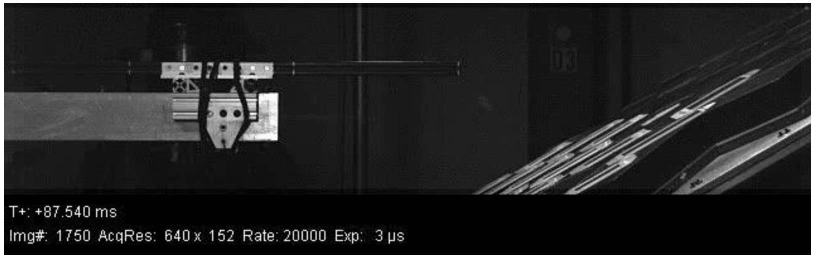
Phantom Cameras

Phantom cameras are high speed digital video cameras capable of recording events at high frame rate. At full resolution of 800 x 600 pixels, the Phantom camera can reach rates of 4800 frames per seconds. For events that requires faster frame rate we can sacrifice resolution for speed. At a 256 x 256 pixels the frame rate can reach 27,000 frames per seconds.

SwRI Impact Test

Target: Shuttle Tile Array
Projectile: Foam
Velocities: 400 to 1,000 ft/sec





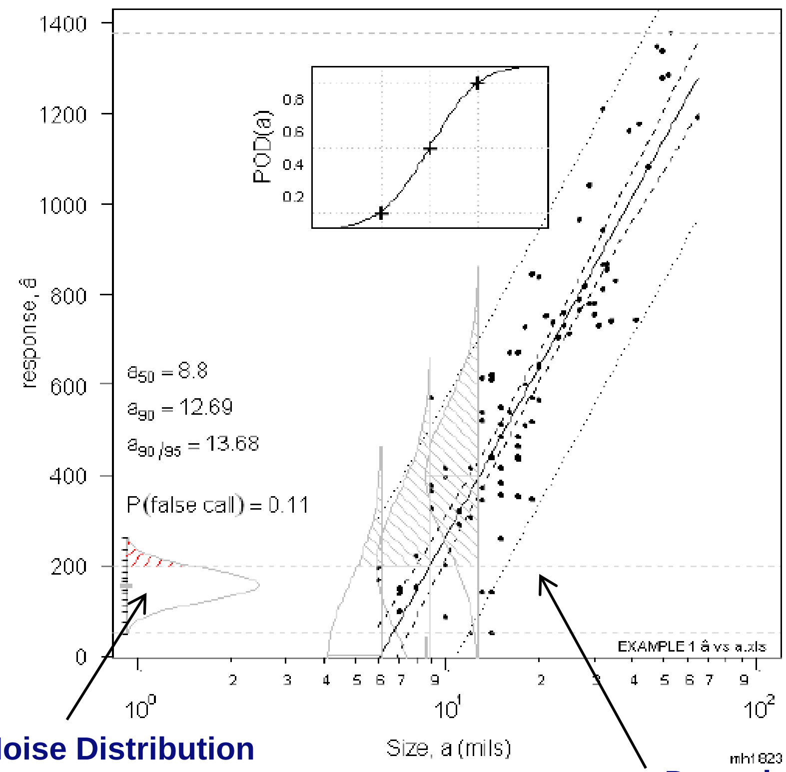
XRF Spectrometer

- Oxford Instruments handheld X-MET5100 energy dispersive X-ray fluorescence spectrometer
- Rapid in-situ chemical analysis of aluminum, titanium, copper, nickel and ferrous alloys
- Spectrum and tabular analysis displays
- Tabular display gives percent concentration of each element and alloy grade
- Emits X-ray radiation; users must take radiation safety training, be approved by the RSO, and wear a dosimeter ring badge

Signal Response POD Analysis per MIL-HDBK-1823

Nondestructive Evaluation Laboratory

Plot of Experimental Data with 90% Data Bounds, Linear Model with 95% Confidence Bounds, and Noise Distribution

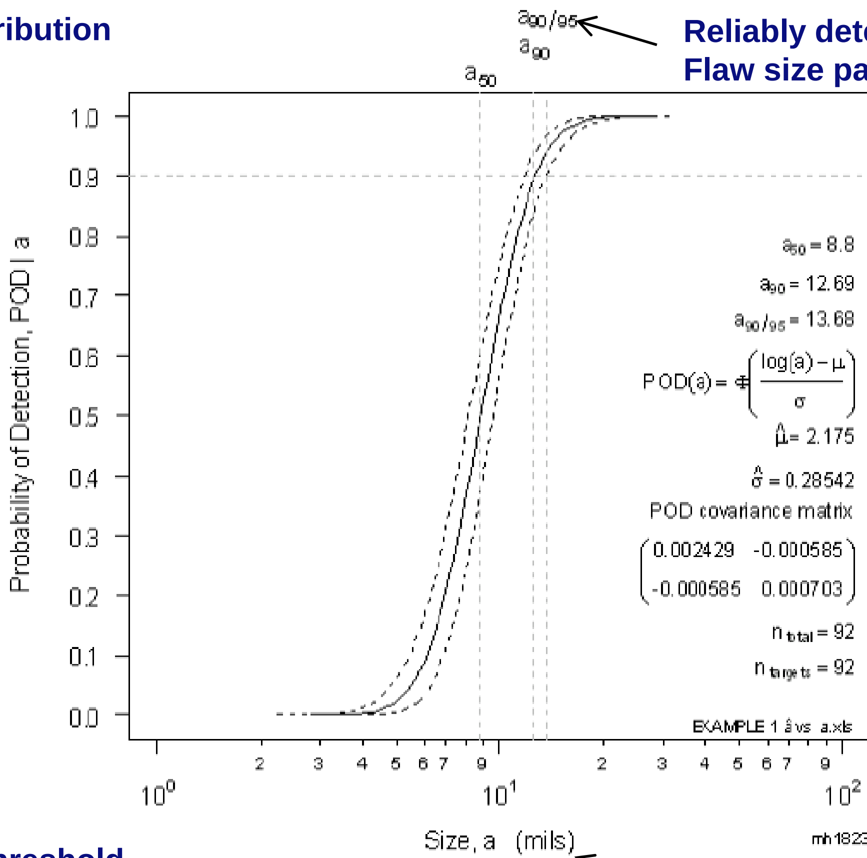


Noise Distribution

Detection Threshold

POD Curve with 95% Confidence Bounds.

Reliably detected Flaw size parameter



Flaw Size Parameter

See following paper for example of POD analysis.
The Critical Role of High Resolution X-ray Micro-computed Tomography for Ultra-thin Wall Space Component Characterization, D. J. Roth, R. W. Rauser, R.R. Bowman, R.E. Martin, A. M. Koshti, and D. S. Morgan, Materials Evaluation, March 2014, page 383.

Standard NDE 90/95 Crack Sizes

U. S. CUSTOMARY UNITS (inches)

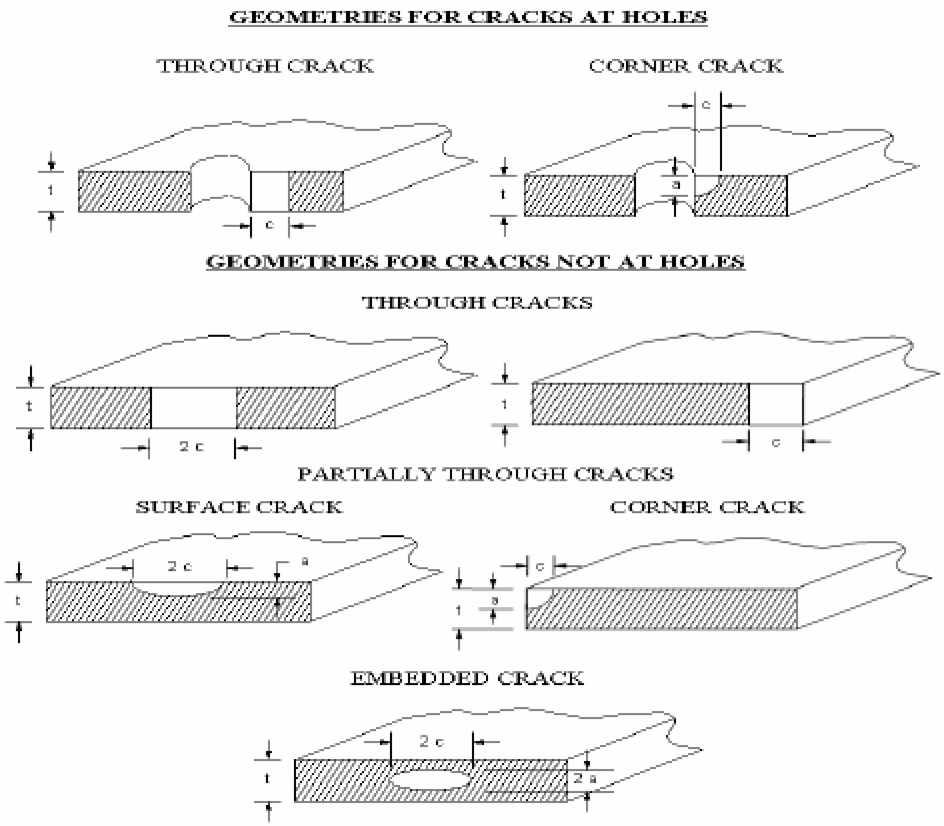
Crack Location	Part Thickness, t	Crack Type	Crack Dimension, a*	Crack Dimension, c*
		Eddy Current NDE		
Open Surface	t ≤ 0.050 t > 0.050	Through PTC[1]	t 0.020 0.050	0.050 0.100 0.050
Edge or Hole	t ≤ 0.075 t > 0.075	Through Corner	t 0.075	0.100 0.075
		Penetrant NDE		
Open Surface	t ≤ 0.050 0.050<t <0.075 t > 0.075	Through Through PTC	t t 0.025 0.075	0.100 0.150 - t 0.125 0.075
Edge or Hole	t ≤ 0.100 t > 0.100	Through Corner	t 0.100	0.150 0.150
		Magnetic Particle NDE		
Open Surface	t ≤ 0.075 t > 0.075	Through PTC	t 0.038 0.075	0.125 0.188 0.125
Edge or Hole	t ≤ 0.075 t > 0.075	Through Corner	t 0.075	0.250 0.250
		Radiographic NDE		
Open Surface	t ≤0.107 t > 0.107	PTC PTC Embedded	0.7t 0.7t 2a=0.7t	0.075 0.7t 0.7t
		Ultrasonic NDE Comparable to a Class A Quality Level (ASTM-E-2375)		
Open Surface	t ≥ 0.100	PTC Embedded**	0.030 0.065 0.017 0.039	0.150 0.065 0.087 0.039

[1] PTC - Partly through crack (Surface Crack)

* See figure 1 for definitions of "a" and "c" for different geometries.

** Equivalent area is acceptable, ASTM-E-2375 Class A.

Taken from NASA-STD-5009



Method Selection Factors

- Each NDE method and technique has its advantages and disadvantages
  - No one method or technique will work for every application
- In fact, two or more complementary methods are often required to ensure a complete inspection
  - For example, critical welds require:
    - Visual inspection to verify weld size and geometry
    - Penetrant inspection for surface flaws (cracks and porosity)
    - Radiographic inspection for subsurface flaws (lack of fusion, lack of penetration, inclusions, porosity and slag)
- Selection of the best method or combination of methods requires a clear understanding of the inspection problem and careful consideration of a number of technical and nontechnical factors
- Ultimately, the chosen method must be validated against standards containing real or simulated flaws
  - Depending on the requirements, validation may require evaluation of the probability of detection (POD) for a specified flaw size

Method Selection Factors

- When a method is not specified by a requirements document, method selection is based on the following factors:
  - Material
    - Metal, nonmetal or composite
    - Homogeneous or heterogeneous
    - Conductive or nonconductive
    - Magnetic or nonmagnetic
  - Fabrication Method
    - Rolled, forged, cast, extruded, powder metallurgy, injection molded
    - Heat treatment, grain size
    - Welded, brazed, bonded
  - Origin and Type of Flaw
    - Manufacturing or in-service
    - Surface or subsurface
    - Planar or volumetric
  - Flaw Location and Orientation
    - Near surface or far surface
    - Parallel or perpendicular to the part surface
    - Direction of maximum stress
  - Flaw Size
    - What size flaw can we safely miss? (Not, how small can we find?)

Method Selection Factors

- Part thickness, size and geometry
- Surface condition
  - Smooth or rough
  - Porous or nonporous
  - Plated, coated or bare
  - As welded or machined flush
- Accessibility
  - In-place or disassembled
  - One sided or two sided
  - Direct or indirect access
- Part Criticality
  - Critical or noncritical
  - High or low stress
- Permanent Inspection Record or Pass/Fail
- Type of equipment available
- Availability of Trained and Certified Personnel
- Time Available
- Cost

Online Resources

- The NDT Resource Center website (http://www.ndt-ed.org/EducationResources/CommunityCollege/communitycollege.htm) offers online training courses in:
  - Penetrant Testing
  - Magnetic Particle Testing
  - Eddy Current Testing
  - Ultrasonic Testing
  - Radiographic Testing
  - Acoustic Emission Testing
  - Infrared/Thermal Testing
  - Remote Field Testing
- The Olympus website (http://www.olympus-ims.com/en/knowledge/) offers training and application information on several methods, including phased array ultrasonic testing and eddy current array testing

JSC NDE Team

1st from left: Ajay Koshti, 2nd from left: Ovidio Oliveras, Center: Norman Ruffino, 2nd from right: David Stanley, 1st from right: Michael Tipton . Morpheus in the background.